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RADC-TDR-63-190

April 1963

Technical Note #4

HIGH FREQUENCY TUNNEL DEVICE STUDY

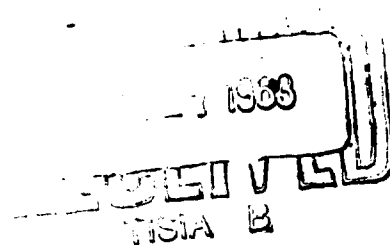
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Contract No. AF30(602)-2673

Prepared for

Rome Air Development Center
Research and Technology Division
Air Force Systems Command
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Griffiss Air Force Base
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ABSTRACT

The work reported here is aimed at investigating the feasibility of achieving low noise microwave amplification - specifically: 20 db gain, 6 db noise figure at 10 kMc, and 1 kMc bandwidth - by using tunneling. It has been concluded that the most promising approach to achieving these objectives is through the use of a thin film cathode operating in conjunction with a microwave structure.

At present, it is possible to build tunnel cathodes which exhibit sufficient current density to permit their use in a 10 kMc traveling-wave tube. However, the life of the cathodes under both dc and pulsed operation is by no means satisfactory. For this reason, efforts were directed towards obtaining better stability and life by improving the uniformity and dielectric strength of the thin insulating layer.

To demonstrate the usefulness of tunnel cathodes in a traveling-wave tube, some prototype cathodes were built and incorporated in a suitable gun structure. The focused electron beam was imaged on a phosphor screen. The emission appeared to be quite uniform in this structure as well as in a projection tube image.

Work was continued towards controlling the insulator thickness by ellipsometry.

A tunnel cathode and a 10 kMc traveling-wave tube have been designed.

Exposure to air appears to be quite deleterious to the performance of tunnel cathodes.

Although no efforts have been made to actually construct a 10 kMc tunnel cathode TWT, on the basis of our work to date it appears that such a TWT is feasible. A difficult life problem still exists, and as yet, no statement can be made as to the noise of the device.

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HIGH FREQUENCY TUNNEL DEVICE STUDY

I. Long Term Objectives

The work reported here is aimed at achieving low noise microwave amplification—specifically: 20 db gain, 6 db noise figure at 10 kMc, and 1 kMc bandwidth—by using a thin film cathode in conjunction with a microwave structure. The thin film cathode shall be operated under dc conditions to emit a steady electron beam of low initial noisiness. The resultant beam will be passed through a microwave structure where it will interact with an electromagnetic excitation, as in a conventional traveling-wave tube.

II. Work Performed During the Period Covered by the Report

1. Outline of Objectives and Approaches

At present, it is possible to build tunnel cathodes which exhibit sufficient emission density to permit their use in a 10 kMc traveling-wave tube. However, the life of the cathodes under both dc and pulsed operation is by no means satisfactory. For this reason, further efforts were extended to obtain better stability and life by improving the uniformity and electric strength of the thin tunneling insulator layer, and by providing a more advantageous metal substrate. Some of the resulting cathodes were investigated for improvement in performance.

To demonstrate the usefulness of tunnel cathodes in a traveling-wave tube, some prototype cathodes were built and incorporated in a suitable gun structure. The focused electron beam was made visible on a phosphor screen. Preliminary tests on the uniformity of the emission from a tunnel cathode were made in a projection tube. This latter test is very important in determining whether the lateral voltage drop across the top metal film causes uneven loading of the cathode area, and whether the stability of the devices is related to spotty emission.

Work was continued towards controlling the insulator thickness by ellipsometry.

To obtain additional confirmation of results achieved with the operating model outlined in the previous report, the study of the velocity distribution of the emitted electrons is very important. A setup has been prepared and subjected to preliminary tests to display the velocity distribution on the screen of an oscilloscope.

In removing completed tunnel cathode structures from the vacuum in which they were made and fitting them into a piece of test apparatus, such as a projection tube or a gun structure, which has a different vacuum, with an intermediate exposure to air, it was observed that the emission deteriorated by one or two orders of magnitude. Possible causes of this effect were traced.

The prototype cathodes built so far have been designed somewhat larger than necessary for use in an X-band TWT. From the experience gained with these cathodes, a design of an X-band TWT has been made. A suitable shape and size for the substrate of this tunnel cathode has been established on the basis of mechanical design and ease of fabrication.

2. Results of Work Performed During the Report Period

A. Fabrication of Tunnel Cathodes

1) Fabrication of Cathodes for Use in a Microwave Tube

About 20 single prototype cathodes were fabricated and tested. The decision to use the larger size was made because of the availability of a setup for measuring the noise generated by the cathodes, and for testing their behavior in a focusing arrangement. Furthermore, the prototype cathode is somewhat easier to fabricate than the smaller X-band cathode. The dimensions of both cathodes were discussed in Technical Note #3. The arrangement of the prototype cathode can be seen from Figure 1. The substrate is an optically-finished pyrex button of 10 mm diameter. The hole in the center of the button serves for feeding through a connection to the surface metal film from the back of the cathode. Protruding contacts and wires in front of the cathode must be avoided in order not to interfere with the gun structure.

One face of the pyrex button is covered with heavy aluminum film of about 2000-3000 Å thickness on which the masking and tunneling oxide layers are grown by anodic oxidation. In order to establish the various oxide thicknesses, a photomasking process is used, as described in earlier Technical Notes. It has been pointed out that the formation of a clean and well defined image of the emissive area requires an exact control of the variables involved in the photomasking, such as thickness of lacquer coating, exposure, baking, development, etc. The problem of getting an even coat of lacquer for the relatively small button has been solved by inserting the buttons into the tightly fitting hole of a polished metal disk of two-inch diameter for the dipping process. For the oxidation, a special jig permits the complete immersion of the button into the electrolyte while making electrical contact only to a very small area at the outer edge of the button.

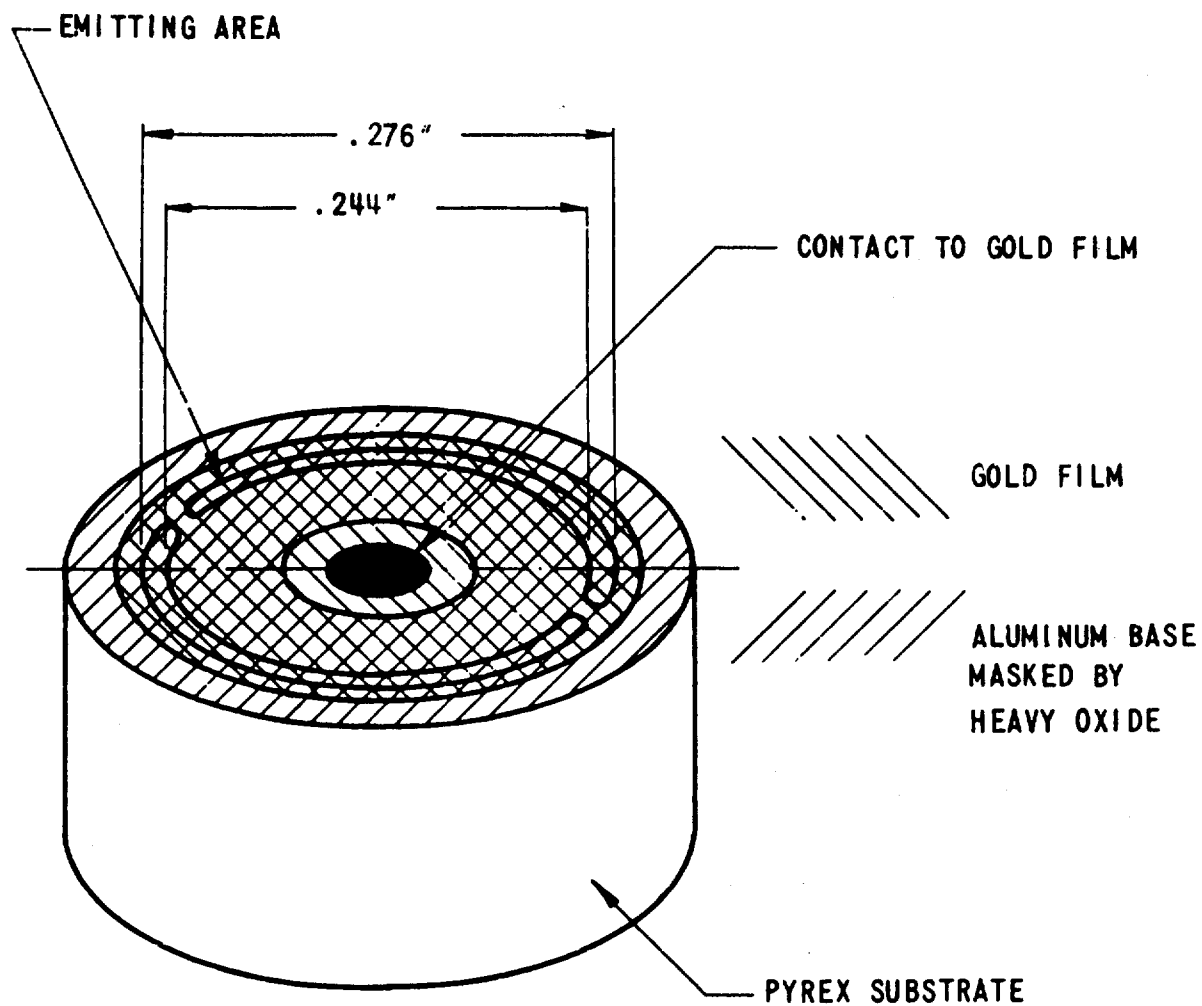


FIGURE 1 PROTOTYPE TUNNEL CATHODE

To provide contact to the gold film on the surface of the device, a small wire is fed into the hole of the button and fixed with gold conducting-cement, which fills the hole flush with the device surface. A problem was encountered with the edge of the hole. In earlier devices, the aluminum film covered the whole surface of the button. In order to prevent shortcircuiting from the gold film to the aluminum at the hole edge, the aluminum was coated with photo-lacquer before applying the conducting cement and evaporating the gold. However, it was discovered that this procedure did not produce the desired effect since the gold cement frequently shortcircuited to the aluminum. This was confirmed by coating an aluminum film on a microscope glass slide with photolacquer and baking it for an hour at 120°C. Subsequently, small drops of gold conductive-cement were deposited onto the lacquer. In all cases, a short circuit to the aluminum was observed, indicating that the solvent of the conductive paint probably softened the photo-lacquer and made it possible for the gold particles to penetrate through the lacquer. Even baking the photolacquer at 200°C for an hour before applying the gold cement did not produce a reliable protection. In view of this, a small mask was attached to the buttons during the process of aluminum evaporation to keep the area around the hole clear. It was still found advisable to protect the edges of the aluminum film with lacquer before the gold evaporation. No failures due to the above-mentioned causes were observed after these modifications.

For the evaporation of the gold, a jig accommodating up to seven devices has been constructed. This jig permits the electrical testing of the cathodes after their completion to allow selection of the cathodes which perform sufficiently well to warrant their use in further experiments. Furthermore, this arrangement permits the monitoring of the deterioration of device performance, which, in many cases, occurs when the cathodes are exposed to air, for example, by transferring them to another test set-up.

2) Base Preparation

Although metal films have the advantage that "flat" surfaces can be prepared with relative ease, their use as a base for the cathode does not seem to be satisfactory. The aluminum films used so far are not completely flat on a microscale, but are composed of small crystallites. This structure may lead to preferential emission of electrons from certain points, which may be enhanced by the structure of the oxide layer as it is related to the structure of the metal base. Possible mechanisms for destruction of the devices under the influence of the requisite high electric fields are heat generation and migration of metal atoms into the insulator. Metal films have the added disadvantage of exhibiting recrystallization as the temperature is increased. This recrystallization can cause cracks in the oxide, leading to the ultimate destruction of the device. Moreover, the recrystallization of films does not allow the formation of insulating layers by thermal oxidation at elevated temperatures.

To diminish these effects, a solid metal base, preferably of single crystal structure, should be advantageous. Therefore a major effort has been initiated to obtain surfaces on single crystal and polycrystalline aluminum of the best possible finish. The polishing procedure can be separated into two different steps: mechanical polishing and electropolishing.

The mechanical polishing involves the use of rough and fine paper, and of "Microcut" on the polishing wheel. The final mechanical polishing is performed with Alpha Alumina #2 on a silk cloth. A thorough degreasing completes the procedure.

For the electrolytic polishing, two different solutions have been tried. The first, the "Alcoa Solution," has the following composition:

| | |
|-----------------|---------------|
| Phosphoric acid | 40% by volume |
| Glycerol | 35% by volume |
| Water | 25% by volume |

The current density used is about 35-40 amps/ft² at a voltage of some 35 volts. The bath temperature is 65°-80°C (ref. 1). The second solution is described in ref. 2 and consists of:

| | |
|-----------------|-----------------|
| Phosphoric acid | 72.4% by weight |
| Sulphuric acid | 12.8% by weight |
| Chromic acid | 8.4% by weight |
| Water | 6.4% by weight |

Here, the current density ranges from 75-150 amps/ft² at a voltage of 15 volts. The bath temperature is kept at 90°C. The proper adjustment of the different variables was found to be of rather critical influence on the final results. Also, a properly induced motion of the piece to be polished parallel to its surface can greatly aid the obtaining of a smooth, bright, and unpitted surface. A vital factor in the whole procedure is the kind of aluminum used. It must be ultra-pure (99.99% Al). Furthermore, it was observed that rolled aluminum did not give as good results as cast aluminum. The best finish could be obtained with single crystal aluminum. The second solution gave the more satisfactory results. At present, more work is necessary to perfect these techniques before polished aluminum substrates are satisfactory for devices, and before the performance of the latter leads to a definite conclusion about the value of these efforts.

3) Preparation of Tunneling Films

As was mentioned in the previous paragraph, providing an improved base should also lead to a more satisfactory oxide film. When a well polished aluminum surface becomes available, it

should be possible to subject it to a sufficiently high temperatures to grow an oxide film of the desired thickness (50-100 Å) which is not possible with aluminum films.

With respect to the anodic formation of the oxide, steps have been undertaken to improve their quality by better control of the process. In anodic oxidation, care must be taken not to bring up the voltage too rapidly. Otherwise, a voltage may exist between the base metal and the solution which momentarily exceeds the destructive breakdown voltage for weak spots in which the oxide has not grown properly, because of conditions imposed by the surface or by impurities. This destructive breakdown can amplify to a great extent the effects of irregularities in the oxide growth. Anodic oxidation may be performed by applying the full voltage instantly, with a limiting resistor in the circuit; however, this does not seem to be a good method for the reasons just given. Early in our experiments, the voltage was brought up slowly, but rather irregularly, by manual control within a period of about five minutes. Now a motor control is used, which raises the voltage very evenly, and the time allotted for the oxidation is fifteen minutes. Since instituting this method, the stability of the tunnel cathodes and their life have been improved significantly.

B. Stability, Uniformity, and Life of Tunnel Cathodes

1) Influence of Oxidation Procedure on Tunnel Cathode Performance

To prove that the quality of anodically-produced oxide layers depends on the fashion in which the voltage is applied and over what period of time, the following tests were performed: Of the several units on a common aluminum base, half of the units were anodized to five volts within fifteen minutes with linearly increasing voltage. For the other half, the voltage was raised to five volts within 1.5 minutes and was left at this value for three hours. While the first of the units were very stable and exhibited characteristics as shown in Figure 2 with a five second sweep, the later units performed very erratically and were not useful.

A number of cathodes were prepared by employing oxidation in an ion discharge, as described in the preceding Technical Note. Although initial I-V and emission characteristics looked quite the same, as was experienced with anodic films of the same tunneling voltage, these films deteriorated very rapidly and finally developed a short circuit. It was concluded that the oxide films produced in the discharge were highly porous.

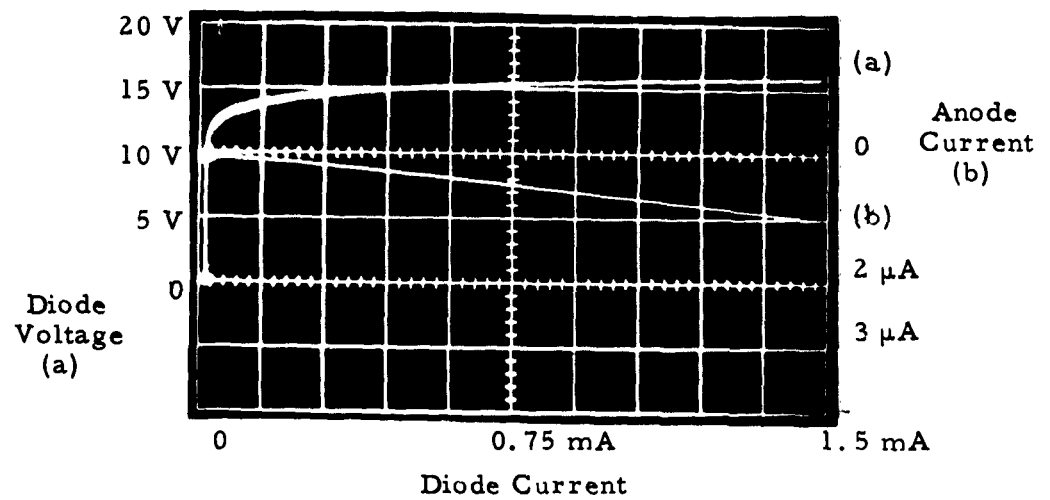


Figure 2. Diode Characteristic (a) and Emission Characteristic (b) of a Unit Prepared with Controlled Anodization

Sweeping Time: 5 seconds

2) Influence of Vacuum System on Uniformity and Stability

In producing the base aluminum film, two different vacuum systems have been employed. One, a 400 l/sec VacIon pump system permitted starting pressures of about 2×10^{-8} torr, and led to pressure rises into the 10^{-5} torr range during the fast evaporation (see previous Technical Notes). The other system is pumped by a 1500 l/sec diffusion pump operating with Dow Corning 704 silicone oil. The system has liquid nitrogen traps in the pump system and a Meissner trap in the bell jar. The starting pressure is in the 10^{-9} torr range and rises to the 10^{-6} torr range during the evaporation. No difference in the general device performance and stability could be determined. However, when several devices produced on the same substrate are compared, the variation in emission for the same diode current generally is smaller for substrates prepared in the VacIon system.

3) Life Time of Tunnel Cathodes

Some life tests under dc loading were performed on units of 10^{-3} cm² active area. The tunneling insulator was produced by motor-controlled anodic oxidation. The results can be seen in Figure 3. The curves show the change in emission current versus time of dc operation for three different levels of diode current densities: 1.5 A/cm², 1 A/cm², 0.5 A/cm², respectively. The lifetime increases roughly proportional to the inverse of loading. However, more tests of this kind are necessary to derive a meaningful statistical picture of cathode failure. After performing the life tests, the diode characteristics were checked. In all three cases, the pronounced bend in the original I-V characteristics had disappeared, and the curves were approaching a straight line.

Under pulsed operation, much larger lifetimes at higher current densities can be obtained. Units of 10^{-3} cm² area with a diode current of 10 mA and an emission of about 30 μ A behaved very stably when driven by rectangular pulses of 0.1 msec duration at a repetition rate of 120 per second. Operation of this type was possible for a period of several hours with no limit established so far.

Annular devices of about $1/10$ cm² active area generally behaved less stably over extended periods than the smaller devices. This may have to do with the larger statistical probability of developing a weak spot in the insulator, and also with the more efficient heat transfer out of the active area for the small devices. A typical example for the behavior of an annular structure is the following: When driven with 1 msec pulses and a duty cycle approaching 10%, the unit delivered 80 μ A with a diode current of 300 mA. This operation lasted for two hours without noticeable change. During the third hour, the emission slowly dropped to 40 μ A.

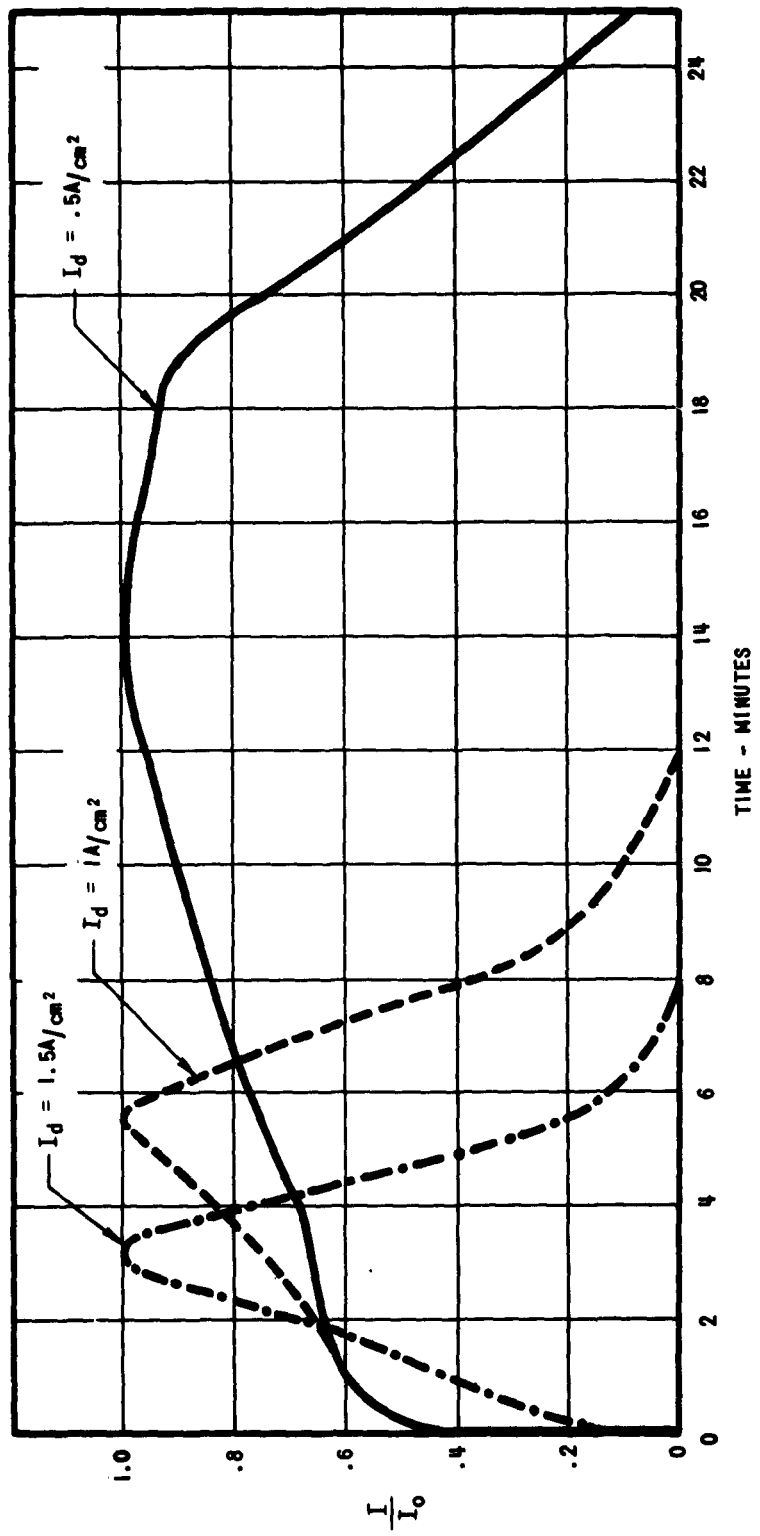


FIGURE 3

4) Influence of Exposure to Air on Tunnel Cathode Performance

For the mounting of tunnel cathodes into test equipment such as a projection tube, a dewar, or an amplifying tube, it would be very convenient if the cathodes could be exposed to air after the vacuum deposition of the gold film. Otherwise, an arrangement for gold deposition must be provided in the test equipment itself.

In transferring cathodes into equipment with intermediate exposure to air, the following experience was gained: Cathodes which were exposed to air for several days after the gold deposition were seen to have lost about 90% of the emission held prior to exposure when tested in equipment with demountable vacuum flanges. Sealing by fusing glass appears to have an adverse effect and reduces the emission even further. The stability of the devices and the shape of the V-I characteristics were not noticeably changed by the exposure to air. In some tests, exposure of the cathodes to air for periods of about ten minutes did not appreciably affect the original emission; however, in other tests, it did.

It is not clear what caused these effects. Perhaps they can be related to differences in the structure of the gold films. In any event, it is advisable to keep the exposure of tunnel cathodes to air as short as possible, to avoid glass melting in setting up equipment, and to use clean pumps in preparing the vacuum. It would be interesting to find out whether moderate baking of the cathodes after their transfer into a new vacuum would have some beneficial effect in driving off contaminants from the cathode surface.

C. Imaging of the Emission Pattern Onto a Phosphor Screen

To determine whether the emission is evenly distributed over the surface of the tunnel cathode, and whether it can be focused by the same arrangements used in connection with thermionic cathodes, a conventional gun structure was built to accept an annular cathode of the type shown in Figure 1. The gun structure was terminated by a willemite screen. The resultant image is shown in Figure 4. The image of the annulus appears in four segments separated by the shadow of the mechanical supports in the gun. For taking the picture, the cathode was operated with 0.1 msec pulses at a repetition rate of 120 per sec. The diode current was 250 mA, the emission 10 μ A. The gold film was 90 Å thick. In spite of the large circulating current, the emission seems to be very even over the width of the cathode. Moreover, the circumferential distribution is quite uniform. The focusing arrangement operates in the proper fashion.

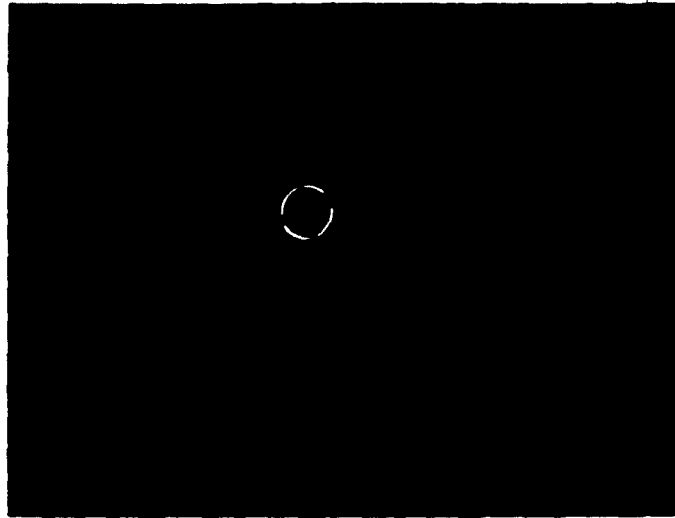


Figure 4. Emission Image of an Annular Tunnel Cathode

In a different setup, the emission image from a circulator dot of 10^{-3} cm² area was magnified by about thirty times and displayed on a willemite screen in a projection tube. A typical picture obtained from this test is shown in Figure 5. As far as can be decided from the limited resolution of the image, the active area is emitting quite evenly. The intensity of emission appears to be strongest in the center. The opposite would be expected if the voltage drop across the gold film were important. The evaluation and further study of these imaging experiments is still in progress.

D. Control of Insulator Thickness with an Ellipsometer

In working with a Rudolph Ellipsometer to measure the thickness of very thin insulator films, several difficulties were encountered. They arose because it was difficult to determine the ellipticity of the light reflected from the film with sufficient accuracy.

In cases of broad light minima, it was found desirable to increase the sensitivity of the photometer delivered with the instrument. Better sensitivity was obtained with a Keithley Model 410 micro-micro ammeter to measure the output of the photomultiplier.

Rather poor extinction of elliptically polarized light has been observed using the Rudolph quarter-wave plate, and considerable difficulty has been encountered in accurately determining the position of the minimum. The substitution of a crude home made compensator (with a Leitz quarter-wave plate) for the Rudolph compensator has given somewhat sharper extinction in the analysis of light reflected from aluminum and chromium surfaces. In order to obtain the desired accuracy in film measurements, the position of analyzer and compensator must be determined with an accuracy of 0.01 degrees. Presently, the accuracy is limited to a value about one order of magnitude larger. Steps are being taken to improve this situation.

Optically flat glass with an index of refraction of 1.5163 has been obtained. If a thin film is placed on this glass, the thickness and index of refraction of this film can be determined by ellipsometer measurements in conjunction with tables published by Vasicek (ref. 4).

E. Velocity Distribution of the Emitted Electrons

Preliminary experiments have been performed to determine the velocity distribution of the electrons emitted from a tunnel cathode. The first setup consisted simply of a planar anode whose distance to the cathode could be varied by means of a bellows arrangement. Starting with a negative potential with respect to the cathode, the anode voltage was increased to 40 volts. The anode current versus anode voltage curve was displayed on the oscilloscope. The cathode was operated

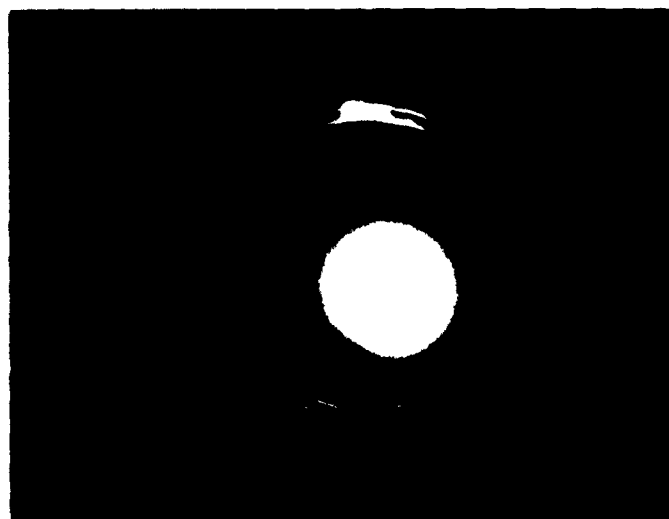


Figure 5. Magnified Emission Pattern from
a Circular Tunnel Cathode
($d = 0.2$ mm)

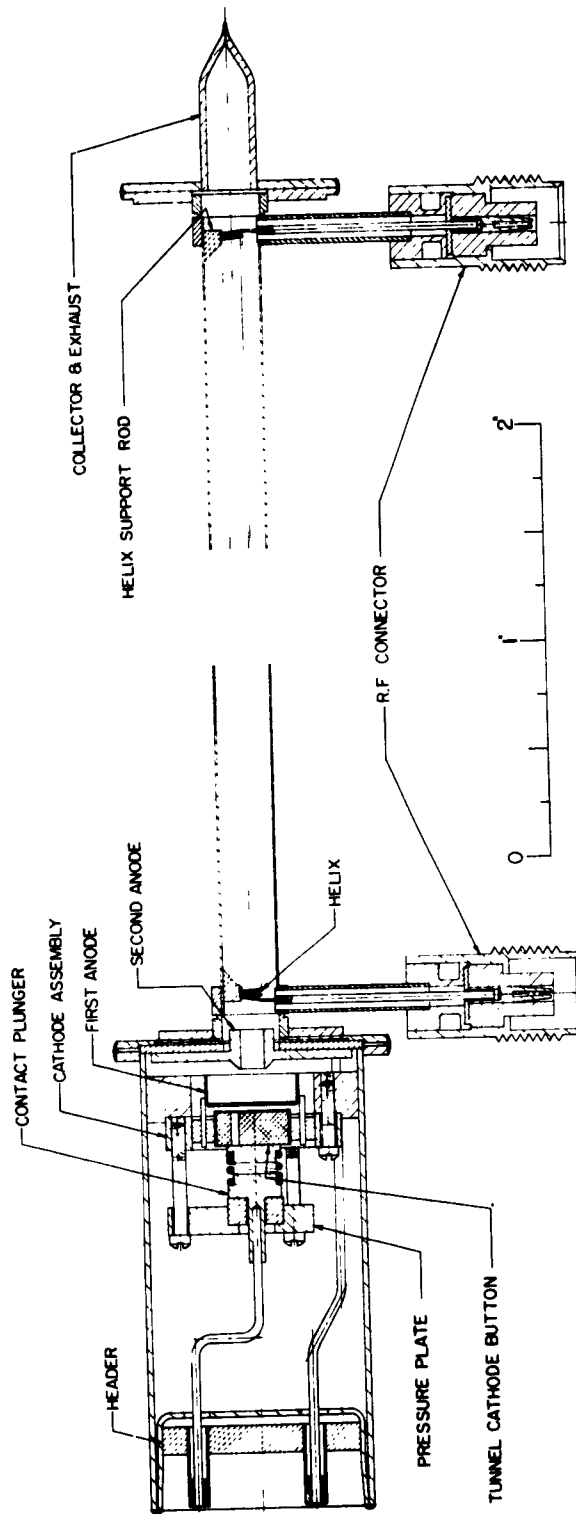
with repetitive 0.1 msec pulses. With the potential of the aluminum substrate as reference, current is expected to be collected at the anode if the anode potential exceeds the work function of the anode. The anode current should saturate if the anode potential exceeds the value $\phi_A + V_d - \phi_{Au}$, which is of the order of 7 volts. V_d is the diode voltage, ϕ_{Au} the work function of the gold = 4.7 eV. The onset of significant anode current (0.01 μ A) was observed for an anode potential of about six volts. However, current saturation was achieved only if the anode potential was increased to about twenty volts at a distance between plate and cathode of 0.5 mm. These conditions became worse with increasing distance. This behavior suggested space-charge difficulties. The maximum saturated current density was 1-10 ma/cm². In order to prevent space-charge effects, a positively biased aperture was placed between the cathode and the anode. However, with this arrangement, difficulties with secondary emission from the anode were encountered. Tests with a modified setup in which the anode plate was replaced by a Faraday cage gave trustworthy results. In a preliminary measurement, the energy distribution of the emitted electrons was found to be close to the expected width of $e(V_d - \phi_{Au})$. The current versus energy spectrum is nearly rectangular for the lower 2/3 of the energy range, and nearly triangular for the upper 1/3 of it.

F. Mechanical Design of an X-band TWT Using a Tunnel Cathode

An X-band tunnel cathode TWT has been designed, as shown in Figure 6, which follows very closely the design of Raytheon's family of low power TWT's. The rf portion of the X-band tube is almost identical to the QKW1085, a ruggedized 10 W S-band TWT. The only exceptions are the pitch of the helix and the length of the helix assembly.

In the construction of the helix assembly, the helix is supported by three quartz rods. Notches along the quartz rods are lap-grooved to match the theoretical pitch desired of the helix. When assembled to the helix, the grooves in the quartz rods ensure precise spacing along the entire length of the helix, reducing discontinuities and resultant power reflections. This helix assembly is inserted into the tube envelope by slightly deforming the thin-walled envelope. The deforming force is removed and the tube envelope clamps tightly against the helix assembly. This method of helix support not only produces a high uniformity of helix pitch, but also maintains this uniformity under conditions of vibration and thermal stress. Excellent thermal conduction from the helix to the tube envelope is provided by this method of fabrication.

The distributed isolation attenuation is derived by coating the proper region of the helix support rods with carbon. This is accomplished by a pyrolytic plating method. The shape of the attenuation distribution is properly tapered to minimize reflections.



X-BAND TUNNEL CATHODE
TRAVELING WAVE TUBE

Figure 6

LEGEND

CERAMIC

GLASS

METAL

The tunnel cathode annulus evaporated and deposited on a pyrex disk is mounted in a cylindrical container. The over-all shape of the tunnel cathode is shown in Figure 7. The container for the cathode is brazed to a ceramic insulator which, in turn, is brazed to a metal ring. The inner diameter of the container is held within tight tolerances with respect to the outer diameter of the cathode assembly. The whole unit is then mounted to a ring which is brazed to the gun envelope. This ring has a small step, the dimensions of which are held within close tolerances with respect to the inner step of the gun mounting flange. A slight taper of the cathode assembly results in an interference fit and thus a means of centering the cathode with respect to the rf structure.

A button, a coil spring, a plunger, and a pressure plate are used to keep the cathode in place. The plunger, insulated by means of a ceramic bushing, is used to make contact to the gold film. The container is used to make contact to the aluminum substrate.

The first anode is supported by three legs a small distance away from the cathode. This anode has an annular aperture.

The second anode is self-jigging and has a circular aperture. It serves mainly as the alignment link between the electron gun and the helix assembly.

A standard header is employed to bring the various leads through the vacuum envelope.

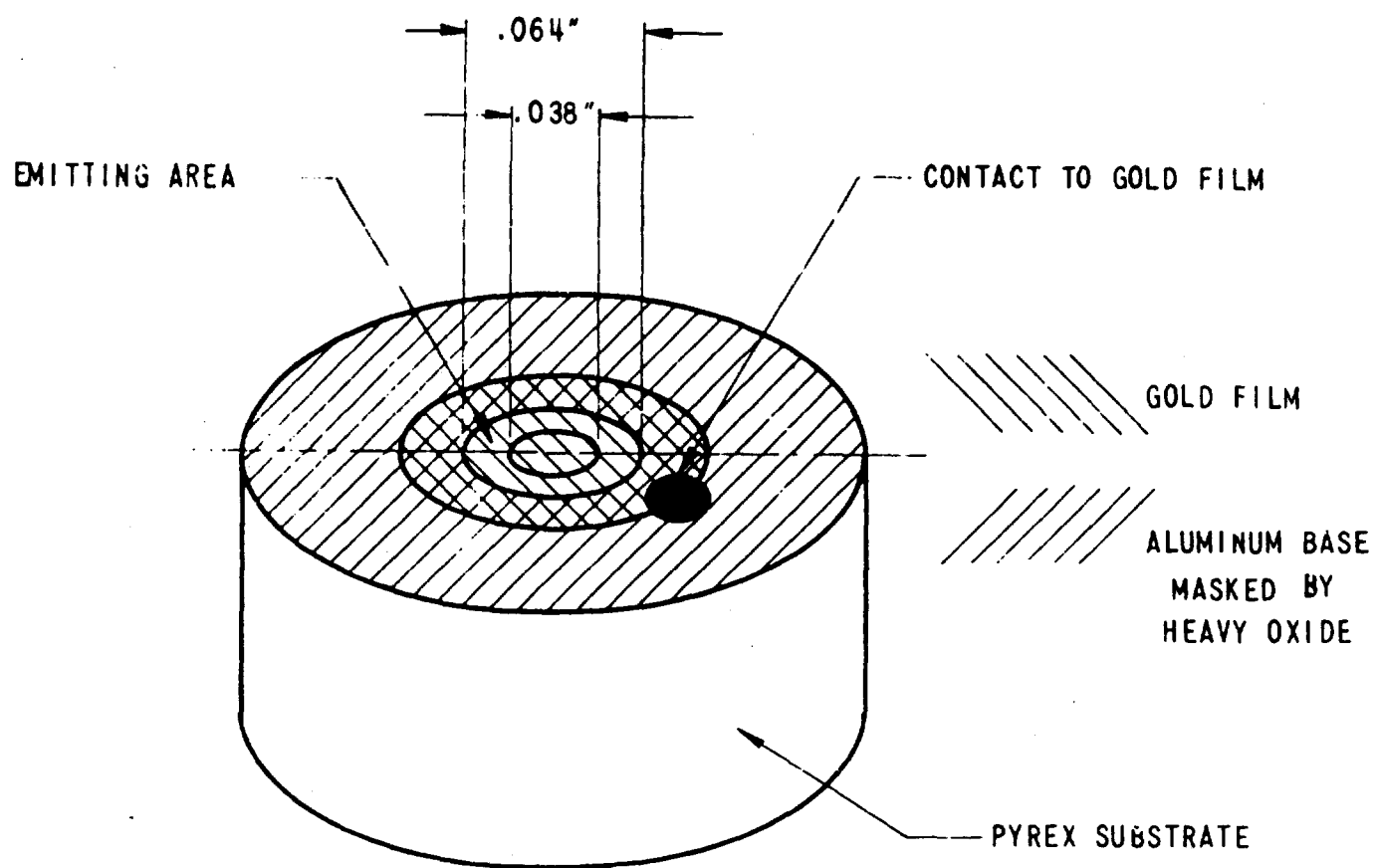


FIGURE 7 TUNNEL CATHODE FOR X-BAND TWT

III Plans for the Next Quarter

During the next quarter it is planned to deliver prototype cathodes and to write the final report.

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| The Bendix Corporation Research Laboratories Division Southfield, Michigan | 1 |
| Hughes Research Labs Div. of Hughes Aircraft Co. 3011 Malibu Canyon Rd. Malibu, Calif. | 1 |

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| <p>AD</p> <p>Raytheon Company, Research Division, Waltham, Massachusetts, HIGH FREQUENCY TUNNEL DEVICE STUDY, by J. Lavine and W. Feist. April 1963. 21 p. incl. illus. 4 refs. (Proj. 4506; Task 450602) (RADC-TDR-63-190) (Contract AF30(602)-2673)</p> <p>Unclassified Report</p> | <p>UNCLASSIFIED</p> <ol style="list-style-type: none"> 1. Tunneling 2. Cathodes, cold 3. Amplifier, microwave 4. Noise, low 5. Films, thin 6. Ellipsometer <ol style="list-style-type: none"> I. Lavin, J. Feist, W. II. Rome Air Development Center, Research and Technology Division, Air Force Systems Command III. AF30(602)-2673 <p>UNCLASSIFIED</p> |
| <p>The achievement of low noise microwave amplification (20 db gain, 6 db noise figure at 10 kMc, and 1 kMc bandwidth) is being studied. The most promising approach is the use of a thin film cathode operating in conjunction with a microwave structure.</p> <p>Tunnel cathodes exhibiting sufficient current density for use in a 10 kMc traveling-wave tube can be built. However, since cathode life under both dc and pulsed operation is by no means satisfactory, efforts were directed towards obtaining better stability and life by improving the uniformity and dielectric strength of the thin insulating layer.</p> | <p>(over)</p> <p>UNCLASSIFIED</p> |

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